



NEW YORK UNIVERSITY  
INSTITUTE OF MATHEMATICAL SCIENCES

25 Waverly Place, New York 3, N. Y.

# AEC Computing and Applied Mathematics Center

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PHYSICS  
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NYO-7981

EXPERIMENTS ON SUPERSONIC PLASMA FLOW  
ALONG MAGNETIC FIELDS

by

D. Finkelstein, M. Ehrlich,  
I. Livingston, and D. Wetstone

March 27, 1958

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## Institute of Mathematical Sciences

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ABSTRACT

Observations are reported of two-dimensional confinement of a vacuum spark discharge plasma in axial magnetic fields up to twenty kilogauss, with supersonic axial plasma velocities observed of two to three centimeters per microsecond. Velocity appeared to increase slightly with field. Confinement up to one meter was observed in experimental tubes down to one inch in diameter. When flux lines were diverted or radially compressed within the tube, the plasma appeared to follow approximately the diverted lines in the manner suggested by theory.



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# EXPERIMENTS ON SUPERSONIC PLASMA FLOW ALONG MAGNETIC FIELDS

## 1. Introduction

This report concerns experiments on some aspects of the general problem of the interaction between magnetic fields and plasma flows. Much of the previous work in this domain has dealt with experiments in which the plasma and most of the magnetic field are produced by the same gaseous discharge (e.g., pinch effect)<sup>1</sup>. With the discovery by Bostick<sup>2</sup> of a simple way of producing high speed plasma flows carrying no net electrical current, the possibility arose of much more flexible experimental arrangements, in which the plasma flow and the applied magnetic field are separately controlled.

Some studies have been made of such flows of plasma across an external magnetic field, both experimental<sup>2</sup> and theoretical<sup>3</sup>. On the other hand, a different collection of questions arises in the case of flow along the external field. (This is not to be confused, of course, with experiments involving axial field ( $B_z$  field) stabilization of gaseous discharge plasmas, which have received considerable recent attention.<sup>1</sup>) For example, can a uniform  $B_z$  field be used to collimate a beam of plasma, and over what distance? What would be the behavior of an injected plasma in regions of converging lines of force (magnetic mirrors), diverging lines of force, or curving lines of force?

It is clear that for an extremely dilute plasma in a strong external field, Alfvén perturbation theory<sup>4</sup> provides answers to these questions. However we are here concerned with the domain of parameters in which the plasma flow acts strongly upon the magnetic field. The result is a self-consistent problem and is more difficult. (See however Ref. 7.)

The effects being studied are sufficiently novel, and the results of similar work in the past have been so unexpected that it was felt worthwhile simply to range quickly over the entire field of geometries suggested by the above questions to see what could easily be accomplished. This exploratory phase is now largely complete and, before proceeding to a more detailed study, we felt it appropriate to report on the kind of experiments that are possible and the qualitative results observed.

The studies reported were begun at NYU in 1955 with techniques acquired from Bostick at Livermore. During the Summer of 1956, the studies were further conducted by Finkelstein, Sawyer, and Stratton<sup>5</sup> at Los Alamos. The present work is a continuation of these investigations.

Some work has also been reported on the use of shock tube methods for producing plasma flows along magnetic fields<sup>6</sup>. In such experiments the plasma advances into a gas-filled tube. In contrast, experiments described here deal with plasmas injected into vacuums of between  $10^{-5}$  and  $10^{-6}$  mm Hg.

## II. Experimental Procedures

The experiments were conducted in evacuated lengths of glass pipe around which were wrapped solenoids to produce pulsed axial magnetic fields. A burst of plasma was injected at one end of the pipe. The various groups of experimental equipment required are described in detail in Appendix I.

The experimental procedures are described in approximately chronological order in this section.

A. Rail Source: Early experiments with the rail source, performed in the 5.1 cm tube, were directed toward obtaining plasma collimation ("plasma pipe"); the question was whether the plasma would expand to the walls of the tube or would be constrained to move along the lines of the  $B_z$  field. The first successful fields were created by employing a one meter steel solenoid of some 75 turns.\* Resistance was of the order of one to two ohms, and the circuit was over-damped.

In most of this series, the  $B_z$  field resulted from 420  $\mu$ F discharged at five kilovolts. Maximum field was attained in 50-60  $\mu$ sec (Fig. 1), with complete discharge in more than 2 msec (Fig. 2). These pictures show the voltage

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\* More precisely, the coil was purchased as a toy, selling by the name of "Slinky."

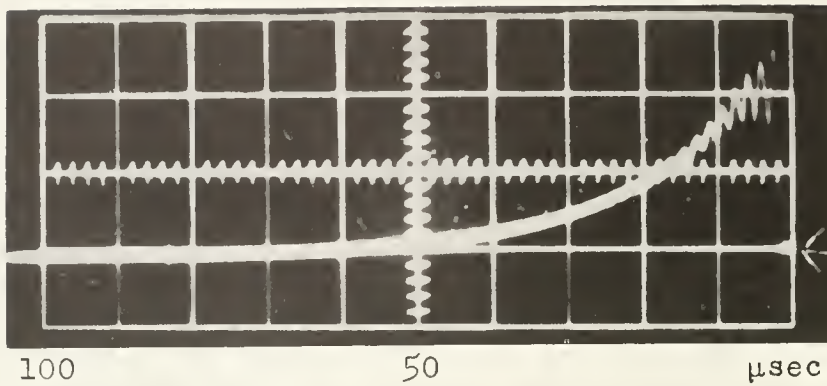


Figure 1

Three-turn search coil output at 50 v/cm on steel solenoid. Bank at 420  $\mu\text{F}$  and 5 KV

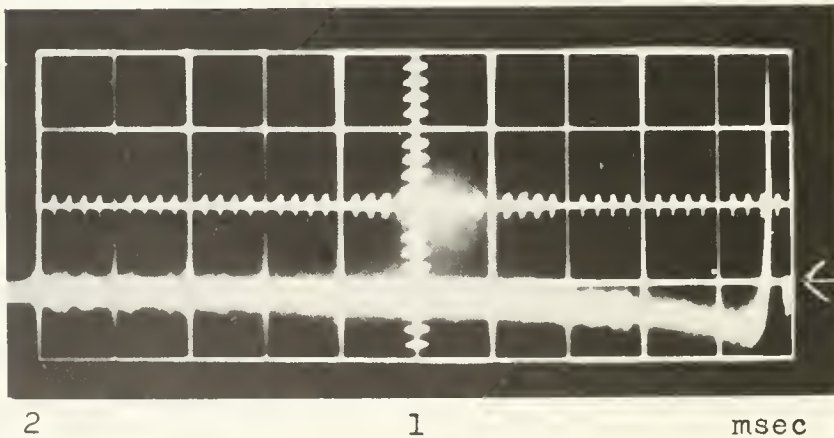


Figure 2

Three-turn search coil output at 5 v/cm on steel solenoid. Bank at 420  $\mu\text{F}$  and 5 KV

induced in a three-turn search coil, wound coincident with three turns of the solenoid and fed into a 10 megohm impedance. The area under the curve to maximum field is estimated to be  $2.1 \times 10^{-3}$  weber-turns, for a total flux of  $0.7 \times 10^{-3}$  webers. Using a solenoid diameter of 2.7" one may estimate an average flux density of about 2000 gauss. This would imply a peak current of about 1900 amperes.

With the 5.1 cm tube the rail source was fired at eight to twelve kilovolts (between 0.8 and 1.7 joules). Photographs were taken of the plasma being fired at maximum field.

The next series employed a 2.3 cm tube. The solenoid was 1/8" diameter beryllium-copper wire. About one-half meter of 36 turns was employed; resistance of a few tenths of an ohm was certainly lower than the inductive reactance of the circuit. A discharge of 300  $\mu$ F at 4.5 kilovolts was determined to reach maximum current in about 65  $\mu$ sec (Fig. 3). This picture shows the voltage induced in a five-turn search coil, wound coincident with five turns of the solenoid and fed into a 10 megohm impedance. The area under the curve to maximum field is estimated to be  $12.2 \times 10^{-3}$  weber-turns, for a total flux of  $2.4 \times 10^{-3}$  webers. Using a solenoid diameter of 1.5" one may estimate an average flux density of about 22,000 gauss. This would imply a peak current of about 27,000 amperes.

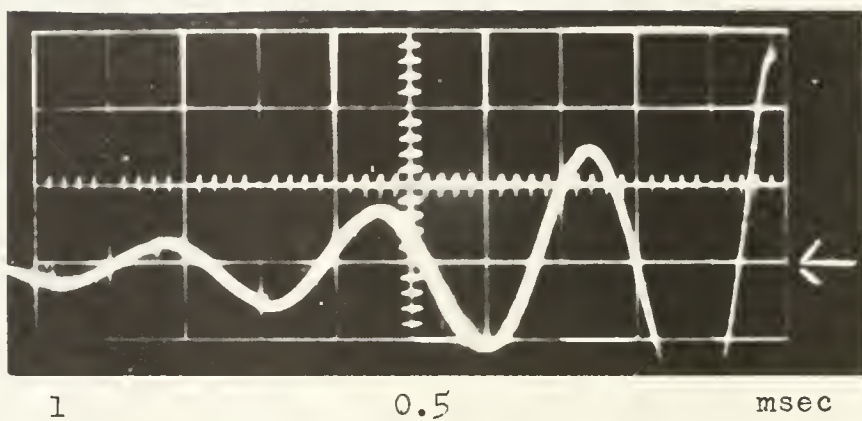


Figure 3

Five-turn search coil output at 100 v/cm on beryllium-copper solenoid. Bank at 300  $\mu$ F and 4.5 KV

With the 2.3 cm tube the rail source was fired at eight to ten kilovolts. Photographs were taken of plasma pipes and magnetic mirrors at maximum field. The mirror experiments used two brass flux-diverters of the shapes shown in Figs. 4 and 5 (and as photographed emplaced in Figs. 25 and 22, respectively). Each diverter was placed axially in the tube, as shown by the dotted lines, about 20 cm from the source (the apex of the cone pointing toward the source). Their diameters corresponded closely to the inner diameter of the tube.

B. Coaxial Source: Work was continued with the 2.3 cm tube, 36-turn copper solenoid, and five-turn search coil. A coaxial source was substituted for the rail source. The capacitor bank conditions were changed to 960  $\mu\text{F}$  at two kilovolts, which produced maximum fields in 115  $\mu\text{sec}$  (Fig. 6). Estimated area under the curve to maximum field is  $7.5 \times 10^{-3}$  weber-turns, for a total flux of  $1.5 \times 10^{-3}$  webers. Estimated average flux density is 14,000 gauss and estimated peak current, 15,000 amperes.

The coaxial source was fired at four kilovolts (0.2 joule). The first studies with this system were made to determine time of flight in the plasma pipe. The photomultiplier telescope assembly was focused at the source and at various distances from the source, and oscilloscope records made of the multiplier output with no field and

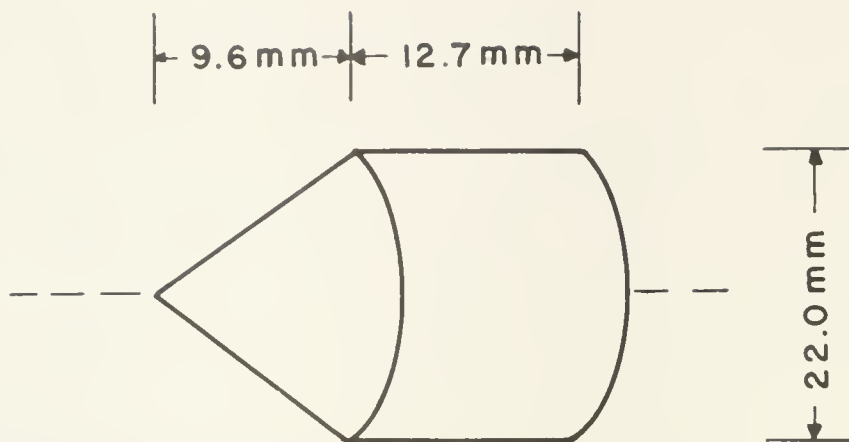


Figure 4  
Flux Diverter: Conic Apex

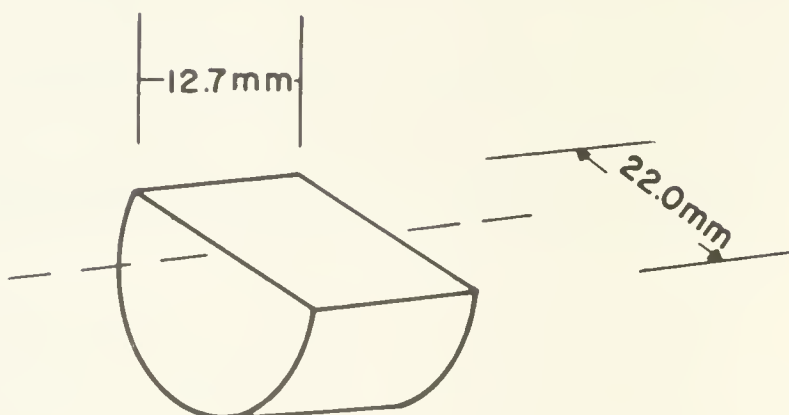


Figure 5  
Flux Diverter: Cylindrical Section

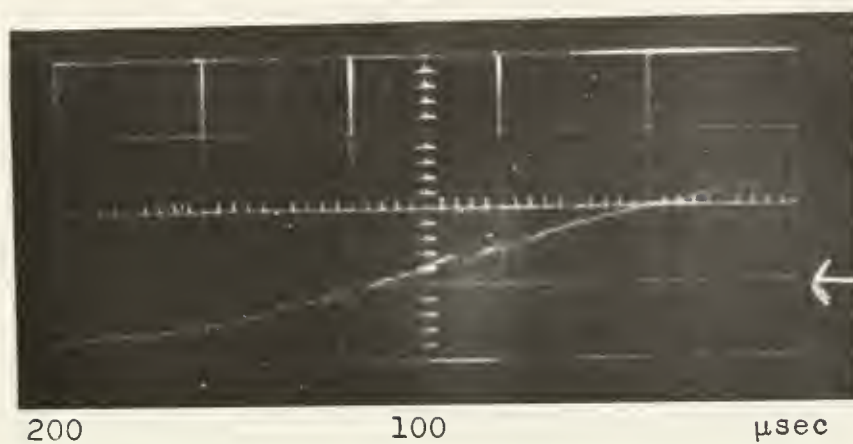


Figure 6

Five-turn search coil output at 100 v/cm on beryllium-copper solenoid. Bank at 960  $\mu$ F and 2 KV

with maximum field. Trigger for these studies was the +30 v pulse generator output (see Appendix I).

A series of photographs was made of the plasma pipe, fired with field at various values from zero to maximum by variation of a pickoff potentiometer in the pulse generator (see Appendix I). The field was estimated in each case by integrating the search coil voltage to the point of plasma discharge, employing the expanded scale trace of Fig. 7. The method of obtaining the actual time of plasma discharge is illustrated by Fig. 33 and accompanying text in Appendix I. The area of the solenoid was taken as  $1.1 \times 10^{-3} \text{ m}^2$  and the calculations yielded average flux density.

Employing the same conditions, each of two flux diverters and a mechanical obstruction were interposed in the plasma path at a distance of 20 cm from the source, and photographs were made of the resulting plasma patterns at various field strengths as before. In one set of measurements a slotted brass ring was employed, as shown in Fig. 8, in which the slot was filled with mica and the entire ring sprayed with acrylic. The centerline again shows axis of orientation with the glass tube of the experiment. In another series of measurements a brass ring of identical dimensions was used without a slot, and in a third series a solid acrylic ring of the same size was substituted.

In all of these observations the photographs were taken

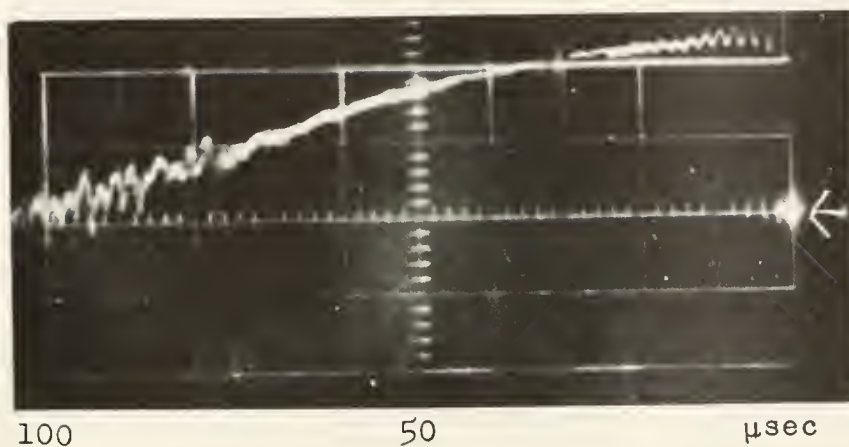


Figure 7

Five-turn search coil output at 50 v/cm on beryllium-copper solenoid. Bank at 960  $\mu$ F and 2 KV

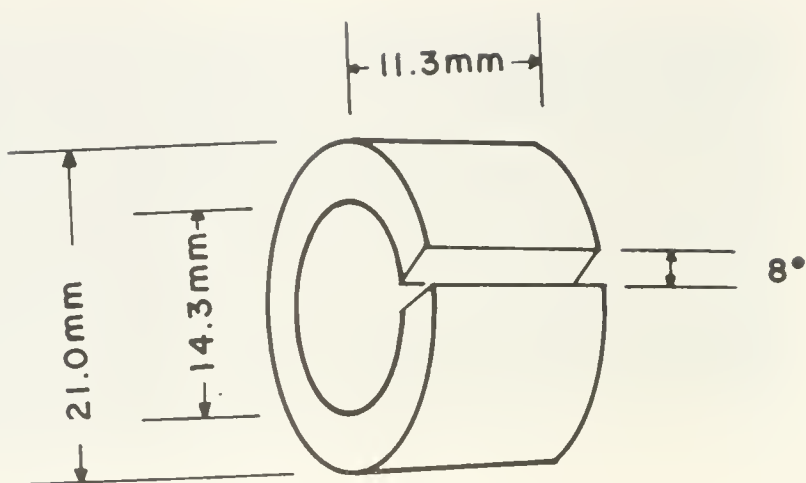


Figure 8  
Flux Diverter: Slotted Ring

with a Land camera and ASA 1000 transparency film.\* A close-up lens set permitted objective distances of nine to fifteen inches which yielded average photographic fields showing 13 cm of tube (Fig. 9), except in the earlier work (5.1 cm tube) in which the entire meter length was photographed also. Lens opening was 4.7 and the camera was opened on "bulb" in a darkened room for a second or two while the plasma was fired. Thus these photographs represent an integrated picture of the plasma recombination light. In a few instances (so identified) multiple exposures were required.

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\* Polaroid Model 110A Camera and Type 46L film.

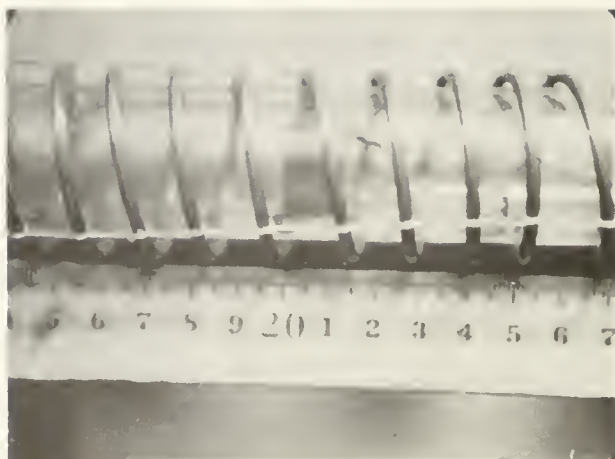


Figure 9

Section of 2.3 cm tube and beryllium-copper solenoid with ring flux diverter emplaced.

Plasma source is 20 cm to the left.

### III. Results and Discussion

The work reported herein may be divided into three categories: plasma pipe, flow into a magnetic mirror, and flow out of a magnetic mirror. The results will be reported in that order. Generally, only one photographic example will be given of each set of conditions. In almost every case, however, the results reported have been obtained repeatedly, particularly any special feature noted in the text.

A. Plasma Pipe: The initial studies in this project were directed toward obtaining confinement of a plasma burst in a straight tube. An 18 cm portion of the 5.1 cm tube is shown in Fig. 10 (the source was 10 cm to the left). A plasma pipe from the rail source with this camera field of view is shown in Fig. 11. It may be seen that the bulk of the recombination light arose from a tube of plasma of roughly one centimeter, despite the fact that the picture is a multiple exposure.

In Fig. 12 most of the 5.1 cm tube is contained in the field of view; Fig. 13 shows a portion of the resulting plasma pipe. Toward the right-hand part of the tube the pipe became lost behind the solenoid supports outside the tube; it appeared that the rail source was firing non-axially. It may be seen, however, that the pipe diameter was again a fraction of the tube diameter.

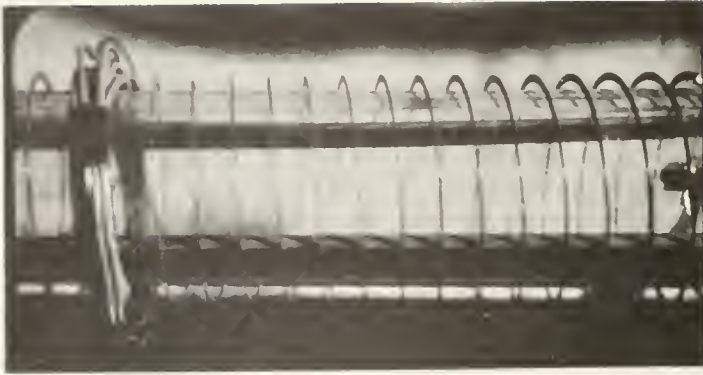


Figure 10

Section of 5.1 cm tube and steel solenoid.  
Source is 10 cm to left of picture



Figure 11

Plasma Pipe. I.

(triple exposure)

Plasma: Rail Source, 1.7 joules

$B_z$  field: 2000 gauss

Vacuum:  $2 \times 10^{-5}$  mm Hg

Chamber: 5.1 cm tube

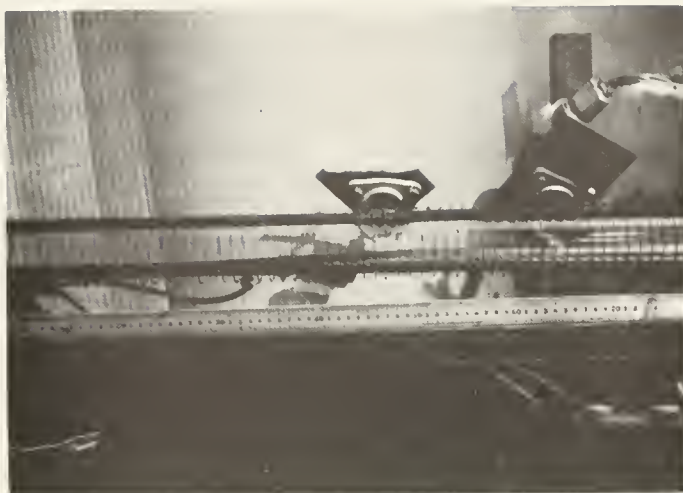


Figure 12  
 Section of 5.1 cm tube and steel solenoid  
 Source is at left edge of picture.



Figure 13  
Plasma Pipe. II.  
 (ten exposures)  
 Plasma: Rail Source, 1.7 joules  
 $B_z$  field: 2000 gauss  
 Vacuum:  $2 \times 10^{-5}$  mm Hg  
 Chamber: 5.1 cm tube

A pipe was formed from the rail source in the 2.3 cm tube also (Fig. 14). Because of the smaller diameter, the plasma collides with the glass tube. The resulting increase in recombination radiation is seen in the figure.

In contrast one may compare the results obtained with this system when the coaxial source was substituted for the rail source. The camera field was as shown in Fig. 9, without flux diverter. Results are shown in Figs. 15a, b, c, and d, representing successively decreasing  $B_z$  field strengths, as noted. Confinement of the main beam of the plasma is strongly suggested, particularly in Fig. 15c. The decrease in emission light intensity (i.e., plasma density) is ascribed to the fact that at lower fields smaller amounts of the plasma remain confined at the point of injection.

Time-of-flight studies were made on the plasma pipe. All measurements in this series were performed in the 2.3 cm tube with the coaxial source at 0.2 joule. An oscilloscope trace was obtained first of the photomultiplier focused directly on the source, as shown in Fig. 16, without  $B_z$  field. All traces in this series were triggered by the square wave output of the pulse generator (see Appendix I). The noted five microsecond delay before initiation of plasma discharge may be seen clearly here. Following this there is at most a two microsecond delay for the plasma to attain maximum light emission.



Figure 14  
Plasma Pipe. III.

Plasma: Rail Source, 0.8 joule

$B_z$  field: 22,000 gauss

Vacuum:  $4 \times 10^{-5}$  mm Hg

Chamber: 2.3 cm tube



15a.  
 $B_z = 14,200$  gauss



15b.  
 $B_z = 13,300$  gauss



15c.  
 $B_z = 9100$  gauss



15d.  
 $B_z = 3000$  gauss

Figure 15  
Plasma Pipe. IV.

Plasma: Coaxial Source, 0.2 joule  
 $B_z$  field: As shown above  
 Vacuum:  $1 \times 10^{-5}$  mm Hg  
 Chamber: 2.3 cm tube

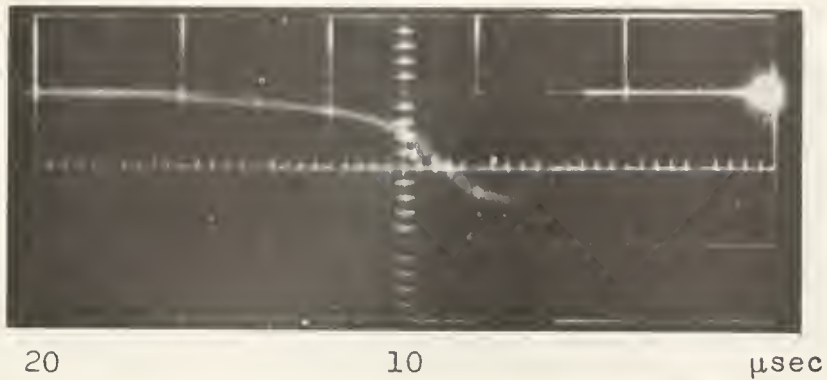


Figure 16

Photomultiplier output at 5 v/cm, looking at coaxial source. No field

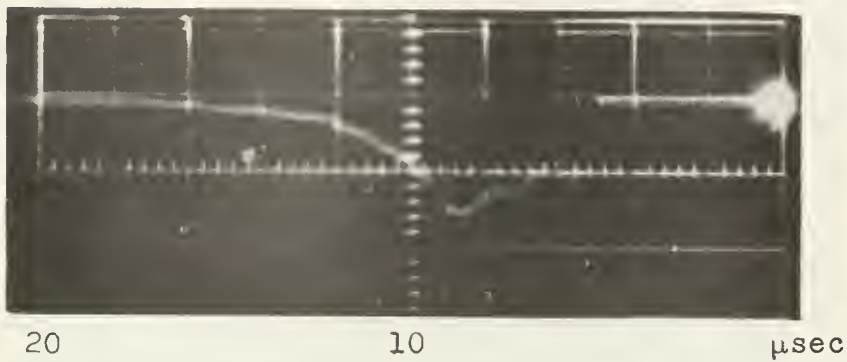


Figure 17

Photomultiplier output at 0.5 v/cm, looking 5 cm from coaxial source. No field

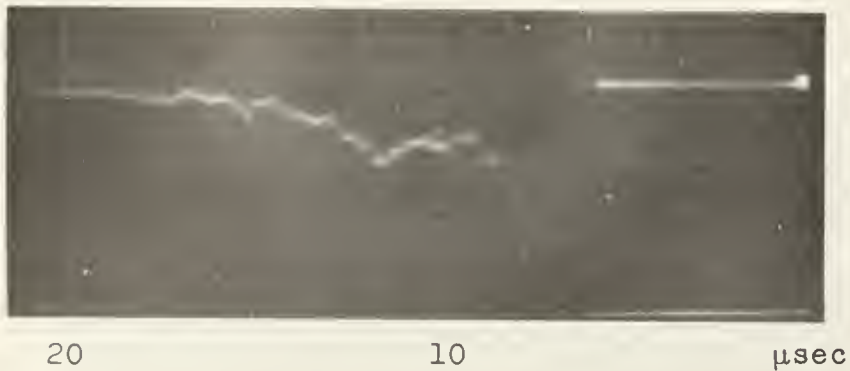


Figure 18

Photomultiplier output at 0.05 v/cm, looking 10 cm from coaxial source. No field

Traces were then obtained with the photomultiplier at five and at ten centimeters from the source, still without  $B_z$  field. These are shown in Figs. 17 and 18 (previous page). Maximum emission was delayed an additional two microseconds in the first case and about four microseconds in the second, for a velocity in each case of  $2.5 \times 10^6$  cm/sec.

With simultaneous application of the  $B_z$  field, velocity appeared to increase. Figs. 19, 20, and 21 show the times for ten, fifteen, and twenty centimeters, respectively, in which the emission maxima were shifted three, five, and seven microseconds. These values denote a velocity of about  $3 \times 10^6$  cm/sec.

B. Flow Into a Magnetic Mirror: As previously described the mirror experiments employed as a flux diverter either a cylindrical section (as a knife edge) or a conic apex (see Figs. 5 and 4). The former is shown positioned in Fig. 22. A burst of plasma from the rail source is shown in Fig. 23; the source was about 20 cm to the left. Two features of this result are of interest. One is the slight upward deflection which that portion of the plasma above the knife edge experienced; this is likely to have been the result of diverted field lines. There appears to be little plasma reflection, using as criterion the lack of appreciable brightening just in front of the diverter. The sharp line which appears to define a density gradient is believed to

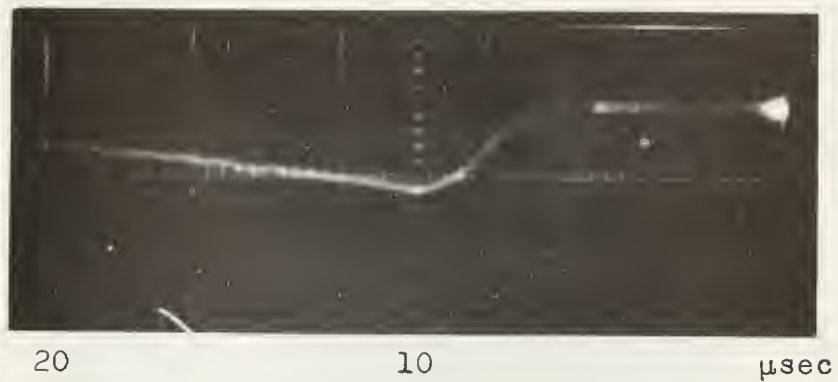


Figure 19

Photomultiplier output at 1 v/cm, looking 10 cm from coaxial source.  $B_z = 14,000$  gauss

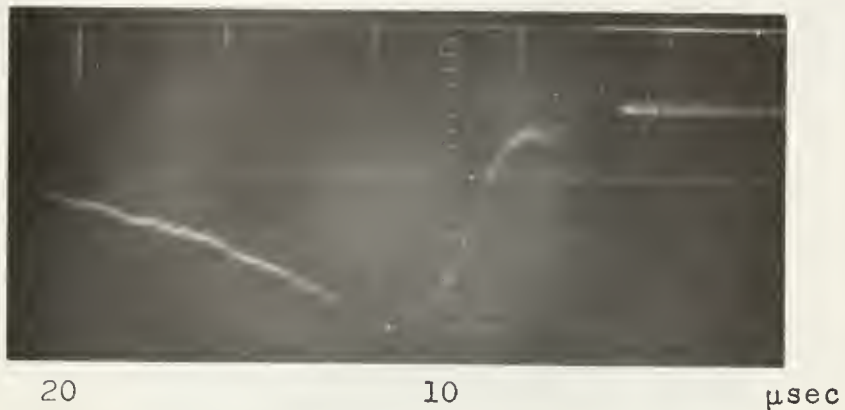


Figure 20

Photomultiplier output at 0.5 v/cm, looking 15 cm from coaxial source.  $B_z = 14,000$  gauss



Figure 21

Photomultiplier output at 0.5 v/cm, looking 20 cm from coaxial source.  $B_z = 14,000$  gauss



Figure 22

Section of 2.3 cm tube and beryllium-copper solenoid, viewing cylindrical section knife-edge slightly from above. Source is 20 cm to the left of diverter.



Figure 23

Flow Into Magnetic Mirror: Knife Edge. I.

(viewed from above diverter plane)

Plasma: Rail Source, 0.8 joule

$B_z$  field: 20,000 gauss

Vacuum:  $4 \times 10^{-5}$  mm Hg

Chamber: 2.3 cm tube

be the near (to the source) edge of the knife, seen because the camera angle was slightly from above. What is important to note, however, is the slightly more dense patch of light near the top of the pipe just above the knife edge (v.i.).

To obtain further delineation of these phenomena the camera was moved downward so as to be level with the knife edge; the result is shown in Fig. 24. Here both plasma reflection and deflection is clearly suggested. Of some interest is the appearance of a sharp line, incorrectly suggesting a shock wave, extending upward just beyond the edge, and one may assume that this was responsible for the light patch high in the previous picture. (This line was not a reflection from the rear portion of a solenoid turn; such reflections may be seen also, though much more faintly, one such being located a few millimeters to the right of the phenomenon in question.) Evidently part of the plasma that strikes the metal obstacle forms a stream directed along the surface of the obstacle, at right angles to the applied magnetic field.

The conic apex is shown emplaced in Fig. 25, about 23 cm from the source. Firing of the rail source is shown in Fig. 26 (the camera had been shifted slightly). Brightening is seen directly before the diverter; no discernable amount of plasma moved beyond.



Figure 24  
Flow Into Magnetic Mirror: Knife Edge. II.  
(viewed on diverter plane)

Plasma: Rail source, 0.8 joule  
 $B_z$  field: 20,000 gauss  
Vacuum:  $4 \times 10^{-5}$  mm Hg  
Chamber: 2.3 cm tube

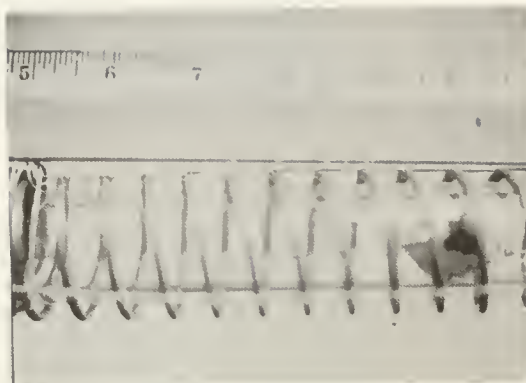


Figure 25

Section of 2.3 cm tube and beryllium-copper  
solenoid, showing conic apex. Source is  
23 cm to the left.



Figure 26

Flow Into Magnetic Mirror: Conic Apex

Plasma: Rail Source, 0.8 joule

$B_z$  field: 20,000 gauss

Vacuum:  $4 \times 10^{-5}$  mm Hg

Chamber: 2.3 cm tube

C. Flow Out of a Magnetic Mirror: The final series attempted to employ flux diverters to obtain a compression of flux lines and a convergent jet. A mechanical obstruction of similar shape was to be used as a control, except that the type of results obtained with the latter object were somewhat unexpected. The geometry of the diverters was shown in Fig. 8. All of this series employed the 2.3 cm tube and the coaxial source. The camera arrangements were as shown in Fig. 9, in which one of the flux diverters is shown emplaced.

The first group of observations employed a closed brass ring to form a short circuit. In principle, field lines should have been excluded from within the ring. Results are shown in Figs. 27a, b, c, and d, representing successively decreasing  $B_z$  field strengths, as noted. Both concomitant mirror effects are in evidence. First, a substantial portion of the plasma was reflected and, second, a small, sharply converging jet appeared in each case on the other side of the ring. Interestingly enough the size of the jet (i.e., the amount of the plasma permitted to traverse the mirror) increased with increasing field. It may be, however, that this greater plasma density in the jet was caused by the increased density of the pipe which approached from the left at higher fields. A small stream



27a.

$B_z = 14,200$  gauss



27b.

$B_z = 13,200$  gauss



27c.

$B_z = 9300$  gauss



27d.

$B_z = 3000$  gauss

Figure 27

Flow Out of Magnetic Mirror: Closed Ring

Plasma: Coaxial Source, 0.2 joule

$B_z$  field: As shown above

Vacuum:  $1 \times 10^{-5}$  mm Hg

Chamber: 2.3 cm tube

of plasma slipped by the top of the ring where about one millimeter or more of space was left.

A group of observations was made under similar conditions utilizing the slotted ring as previously described. It was expected to function as a flux concentrator rather than a diverter, a portion of the flux lines being compressed and constrained to pass through the hole in the ring. Results are shown in Figs. 28a, b, c, and d, representing successively decreasing  $B_z$  field strengths, as noted.

These results differ in both of the concomitant mirror phenomena noted in the previous data. The concentration of field lines, as opposed to diversion, should produce a smaller amount of plasma reflection (consider the relative cross-sections available), although some is to be expected from the positive  $B_z$  gradient. This result was obtained and is particularly evident in comparing, for example, Figs. 27c and 28c, both taken at identical  $B_z$  field strengths. Second, there is little evidence of a convergent jet effect, but rather the plasma appears here to be following the concentrated field lines which spread on the far side of the ring. In fact, close inspection of Figs. 28a and b reveals distinct plasma divergence, starting perhaps five to ten millimeters beyond the ring.

The last group of observations had been originally designed as a set of control experiments, the interposing



28a.  
 $B_z = 14,200$  gauss



28b.  
 $B_z = 13,300$  gauss



28c.  
 $B_z = 9100$  gauss



28d.  
 $B_z = 3000$  gauss

Figure 28  
Flow Out of Magnetic Mirror: Slotted Ring

Plasma: Coaxial Source, 0.2 joule

$B_z$  field: As shown above

Vacuum:  $8 \times 10^{-6}$  mm Hg

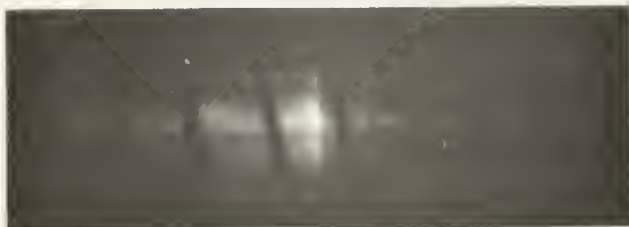
Chamber: 2.3 cm tube

of an acrylic ring of identical shape to the brass ring to serve as a mechanical obstruction. All other conditions were again the same (except the focal distance of the camera had been changed slightly). Results are shown in Figs. 29a, b, c, and d, representing successively decreasing  $B_z$  field strengths, as noted.

As expected, the ring did function as a mechanical obstruction, preventing most of the more tenuous portions of the plasma from passing. The sharp beam in the center was quite unexpected, however, since it was much smaller in diameter than that of the inside of the ring. Also, it may be seen in each case that the beam represents an extension of an undeflected, tight plasma pipe originating on the left.



29a.  
 $B_z = 14,200$  gauss



29b.  
 $B_z = 13,300$  gauss



29c.  
 $B_z = 9300$  gauss



29d.  
 $B_z = 3000$  gauss

Figure 29

Mechanical Obstruction of Plasma: Acrylic Ring

Plasma: Coaxial Source, 0.2 joule

$B_z$  field: As shown above

Vacuum:  $8 \times 10^{-6}$  mm Hg

Chamber: 2.3 cm tube

## APPENDIX I

### Description of Experimental Equipment

The experiments were conducted in evacuated straight lengths of glass pipe around which was wrapped a solenoid to produce a pulsed, axial magnetic field, and into one end of which was injected a burst of plasma. Several groups of equipment were required.

A. Vacuum System: The vacuum system (Fig. 30) included a six-inch, water-cooled diffusion pump with liquid nitrogen trap and ballast tank, a 15 cu ft/min backing pump, and appropriate control and vacuum measurement circuitry.\* This system could attain pressures of  $10^{-6}$  mm Hg within the experiment tube (ionization guage measurement).

B. Axial Field System: The confining field was obtained by the discharge of a capacitor bank through a single layer, linear solenoid surrounding the glass tube (Fig. 31). The bank consisted of up to fourteen capacitors\*\* in parallel or series-parallel arrangement, each rated at 120  $\mu$ F and three kilovolts, and each with a short circuit ringing frequency of approximately 100 kc. Parallel plate connections were employed where practicable, but great care

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\* Vacuum Equipment Division of New York Air Brake Company with Kinney backing pump.

\*\* Sprague Vitamin Q

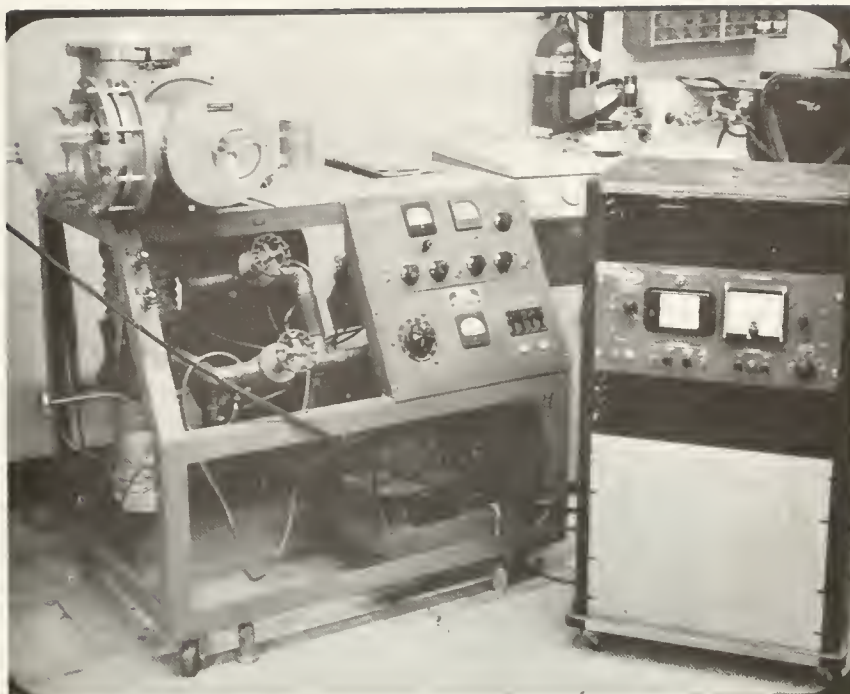


Figure 30  
Vacuum System

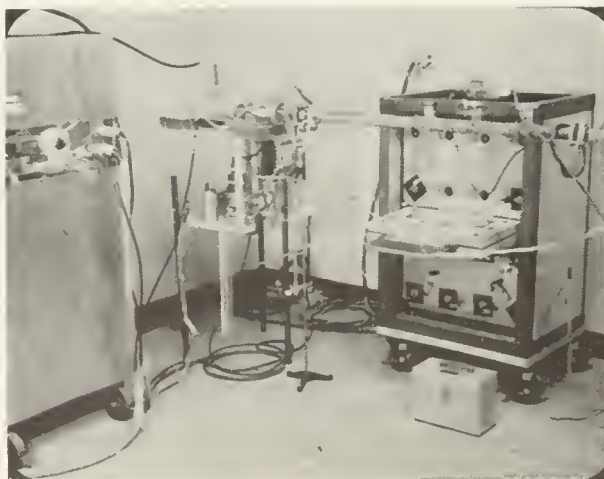


Figure 31  
Power Supply, Firing Circuit, and Capacitor  
Bank, with Experiment Tube

was not taken in reducing external inductance because of the relatively large current-limiting inductance of the capacitors. The bank was switched by a GL-5550/GL-415 ignitron; this was ignited by a 10  $\mu$ F capacitor which was charged by a voltage divider attached to the high voltage line and discharged by relay.

Charging current for the main bank was supplied by a 7 kva transformer, rectified by a full-wave bridge of 8008 tubes, and supplied through 2000 ohms of charging resistance. Two-phase (240 v) primary current was supplied with one leg feeding through a motor-driven powerstat. In this fashion it was possible to charge the bank quite rapidly (1000  $\mu$ F to 3000 v in about four seconds) while requiring no more than 30 amperes of primary current per phase.

The ignitron firing relay was activated by a ten kilovolt meter relay on the control console (Fig. 32) with a variable high limit contact. The usual safety features assured that the system could not be charged and fired unless bridge filaments were hot, meter relay auxiliary circuits were powered, and the powerstat was in its zero position. The main bank was arranged to discharge automatically upon any equipment malfunction or power failure. A high wattage bleeder resistance to ground was provided in case of ignitron failure. Circuits were so arranged that neither

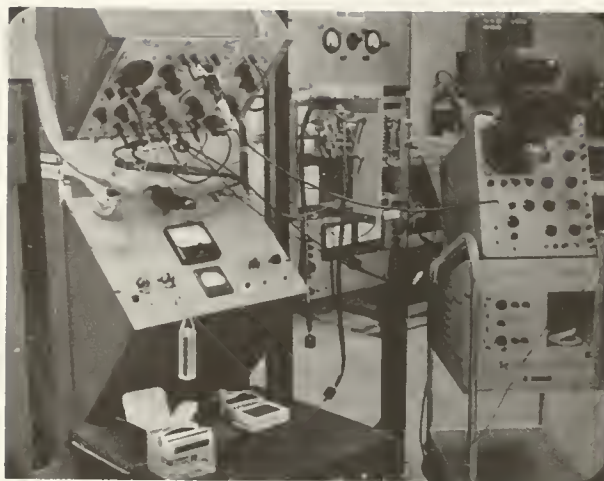


Figure 32  
Control Console

(Firing Master, Waveform and Pulse Generators,  
and Plasma High Voltage Supply)

primary nor secondary power flowed directly to the console, nor could this have been altered by circuit failure.

C. Plasma System: Plasma was created at one end of the experiment tube by discharging a barium titanate capacitor across a plasma source. Both a rail source<sup>2</sup> and a coaxial source were employed. The rail source consisted of two 0.04" deuterium impregnated titanium conductors, set about 0.12" apart and making an angle of ten degrees, in a 0.38" diameter lava button. Twin copper leads were attached to the rear end of the rails, where they protruded from the button, and the entire assembly was potted in epoxy resin. The coaxial source consisted of a 0.25" diameter tinned steel tube containing a conical (45°) ceramic insert, with the point of a 0.03" copper wire inserted to the vortex. This is intended to be the "shaped charge" geometry employed in the technology of explosives. Similar sources have been applied elsewhere<sup>5</sup> for the generation of high velocity plasma bursts.

The titanate capacitor was rated at 0.024  $\mu\text{F}$  and twenty kilovolts, and rang (short circuit discharge) at better than 200 kc with the present arrangement. The firing of the source was triggered by an air-gap spark discharge in the mounting of the capacitor. Charging current was obtained from a thirty kilovolt, 50 va power supply\* and

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\* Beta Electric Corporation

fed through a 40 megohm charging resistor, to produce a one second time constant. The center electrode of the source was negative.

D. Synchronization System: Maximum fields were attained in the order of a hundred microseconds after initiation of main bank discharge. The life of the primary plasma was estimated at not over ten microseconds, however. Therefore, synchronization was required to attain plasma injection at maximum (or selected fractional)  $B_z$  field strengths.

Several turns of search coil were wound coincident with a similar number of solenoid turns; in most experiments this carried an approximately 150 v initial signal (with high impedance load) upon discharge of the main bank (at  $di/dt$  maximum, which occurred in less than two microseconds). In addition to indicating the time of maximum field this signal was used as a trigger to initiate a sawtooth pattern in a waveform generator\*. The sawtooth was next fed into a pulse generator\* where a pickoff potentiometer gated a pulse of variable height and width. The potentiometer was set for the desired elapsed time between initiation of field build-up and firing of plasma.

The output of the pulse generator, after amplification,

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\* Tektronix, Inc., Type 162 Waveform Generator,  
Type 161 Pulse Generator

was used to trigger the barium titanate capacitor. About a twenty microsecond, + 30 v pulse was used to turn on a negatively biased 2D21 hydrogen thyratron. A cathode follower provided a 200 v peak to the grid of a 5C22 hydrogen thyratron. This permitted a 0.1  $\mu$ F, 5 kv capacitor to discharge through a 0.5 meg high voltage resistor. A spark discharge was obtained from the potential drop across the resistor and was used to trigger the plasma source.

In making oscilloscope\* pictures of the shape of the search coil signal it was necessary to superimpose some other signal which would help to locate the firing of the plasma so that the actual point in the field build-up at which the plasma was injected could be determined accurately. This was accomplished by applying the output of the pulse generator (+ 30 v) to the cathode of the CRT, thus providing a blanking signal. This in no way interfered with the main trace, providing that the intensity was properly adjusted. From the photomultiplier studies it was found that there was a five microsecond delay between the initiation of the pulse signal and the beginning of plasma formation, and this delay was included in the synchronization considerations. However, careful examination of the oscilloscope trace obtained

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\* Tektronix, Inc., Type 545, with 53/54K Preamplifier.

in each case, for example Fig. 33, reveals a slight smear in the trace about five microseconds after blanking (at 56  $\mu$ sec), which is undoubtedly noise from the plasma discharge. This provided confirmation of the delay time.

E. Photomultiplier System: The photomultiplier assembly was a thallium-activated sodium iodide crystal and 6292 photomultiplier, powered by a 2500 v supply.\* The photomultiplier was modified for these measurements by removing the crystal and substituting a telescope assembly which was focused on various points along the center of the experiment tube. This arrangement permitted a narrow field of view and also removed the photomultiplier physically from the main axial field.

The impedance of the photomultiplier output was matched to the input of the oscilloscope with 2500 ohms.

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\* Tracerlab, Inc., RLD-2 Gamma Scintillation Spectrometer Detector and RLS-1 High Voltage Supply.

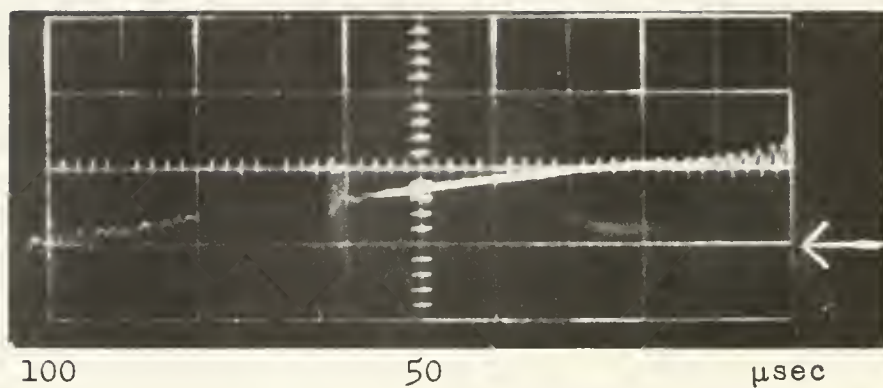


Figure 33

Five-turn search coil output at 100 v/cm on  
beryllium-copper solenoid, showing CRT  
blanking at 56  $\mu$ sec and plasma discharge  
at 61  $\mu$ sec

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